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TECHNICAL ANALYSIS REPORT - AFSWP-503

BASIC CHARACTERISTICS OF THERMAL RADIATION FROM AN

ATOMIC DETONATION

CONFIDENTIAL
FORMERLY RESTRICTED DATA
ATOMIC ENERGY ACT 1954

by

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Regraded

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CONFIDENTIAL
FORMERLY RESTRICTED DATA
ATOMIC ENERGY ACT 1954

November 1953

Headquarters, Armed Forces Special Weapons Project

Washington 13, D. C.

BASIC CHARACTERISTICS OF THERMAL RADIATION FROM AN ATOMIC DETONATION

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SUMMARY

GENERAL

The results of a recent review and analysis of all test data through TUMBLER-SNAPPER on the basic characteristics of thermal radiation from atomic detonations, namely: total thermal energy release, time-intensity, and spectral distribution, are presented for two types of burst: air and surface.

1. Air Burst

a. The basic characteristics of thermal radiation from air burst weapons of yields 1 to 100 KT are now considered to be known with an accuracy of 10 per cent.

b. The total thermal energy released by a 20 KT weapon is 7.4 KT, or 37 per cent thermal efficiency, and it increases as the 0.94 power of the radiochemical yield.

c. The times of the minimum and second maximum intensity scale as the 0.5 power of the ratio of the total yields for all yields greater than 10 KT. It is thought that smaller yield weapons of operational design will also scale. A normalized plot of the thermal pulse shape is given which is the same, within $\pm$ 15 per cent, for all yield weapons above 10 KT.

d. It is postulated that the intensity in the second maximum scales as the 0.5 power of the ratio of the weapon yields. A generalized thermal pulse based on 0.5 power scaling of both time

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and intensity is given.

e. The average color temperature for all bursts is 6000 ± 500° K.

f. It is postulated that these characteristics will prevail for air bursts of all weapon yields up to 10 MT. Although the high yield data are sparse and erratic, they are not obviously in conflict with this postulation.

g. These characteristics apply to an airburst at a height such that the reflected shock wave does not reach the fireball until after most of the thermal radiation has been emitted. Early arrival of the reflected shock distorts the fireball and may reduce the color temperature and the total energy emission of the lower portion of the fireball.

2. Surface Burst (Detonation on the earth's surface)

a. The thermal energy received from a surface burst is approximately one-third that of an air burst of the same yield when the radiochemical yield is less than 250 KT. When the radiochemical yield is 1 MT or greater, the total thermal energy is approximately two-thirds that of an air burst of the same yield. For total weapon yields between 250 KT and 1 MT, the thermal yield may be expected to fall between one-third and two-thirds that of an air burst.

b. The indications are that time of the minimum intensity of the thermal pulse from a surface burst is the same as that of an air burst. The time of the second maximum of a surface burst may

also be the same as that of an air burst. At this time, this is only an assumption based on a 10 MT surface burst and tower shots of various yields which agreed within $\pm$ 20 per cent. Surface detonations of weapons with yields in the megaton range have the same normalized pulse shape as air bursts.

     c. The average color temperature of a surface burst of any yield is approximately 3000° K.

RESTRICTED DATA
ATOMIC ENERGY ACT 1946

BASIC CHARACTERISTICS OF THERMAL RADIATION FROM AN ATOMIC DETONATION

A. INTRODUCTION

a. Over a period of years, basic thermal measurements have been made at all full-scale weapons test series. The majority of tests have been of weapons with yields in the range 1 to 100 KT, with limited tests up to 10 MT. These measurements were made to establish the basic characteristics: total thermal energy, time-intensity, and spectral distribution for a large range of weapon yields, and to determine empirical scaling relationships, usually referred to as scaling laws, to permit prediction of these characteristics for an atomic detonation of any yield.

b. Two agencies, Naval Radiological Defense Laboratory and Naval Research Laboratory, have been the principal participants for the Department of Defense and the Atomic Energy Commission. More recently, the Department of Engineering, University of California, Los Angeles, has conducted such measurements at several shots. In July 1953, working groups from these agencies convened for the purpose of correlating all comparable data. The results of this conference form the basis for this paper.

B. DISCUSSION

1. Total Thermal Energy*

a. The total thermal energy per unit area was measured at

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*The term "total thermal energy" is used to designate the integrated radiant energy emitted by the fireball during the main radiant pulse.

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various distances with a variety of black body integrating instruments at atomic detonations, the total weapon yields* of which varied from 1 KT to 10 MT. These data were corrected for atmospheric attenuation and integrated over a sphere the radius of which was the distance from the point of detonation to the instrument location, to obtain the total thermal energy radiated by the fireball for a given yield weapon.

  b. The instrumentation for this measurement varied, depending upon the agency that made the measurements. In some cases, two or three agencies participated at a single shot; in others, just one was present. A copper disk calorimeter was developed at the Naval Radiological Defense Laboratory for measuring energy per unit area in the range 1 to 50 cal/cm^2 with a time constant of about 20 milliseconds and a 90° field of view. The Naval Research Laboratory project personnel employed highly sensitive thermopiles with 10° field of view, thermocouples, and blackened sphere radiometers (a unique NRL design). The group at the University of California, Los Angeles, used a thermopile of its own design with a time constant of about 15 seconds for the continental shots, and about 15 minutes for the IVY Operation. NRDL's instruments were usually located within a few thousand yards of the fireball for a nominal bomb. NRL's measurements were made at various locations from a few hundred yards to a station approximately 10 miles from detonations at the Nevada Proving

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 * Radiochemical yields, with exception of the Mike Shot, where fireball diameter analysis was used.

Grounds. UCLA's instruments were designed primarily for aircraft installation, 10 to 20 miles distant.

c. The type and magnitude of the corrections applied to the data before calculating the total thermal yield were dependent upon the distance and location of measurement and the transmission properties of the atmosphere. In the past both NRDL and NRL's data were corrected for atmospheric attenuation as determined by actual transmission measurements. In addition, NRL's data were corrected for the energy received by scatter, as a function of the field of view. The scatter correction was assumed to be negligible for NRDL's data, since it was obtained at distances that were small compared to the visibility.

d. In comparing the results of these agencies, when more than one participated at a shot, certain discrepancies were found. In some instances the difference between estimates of thermal yield was 25 per cent or more. Since the inherent error in each instrumentation system is estimated to be ±10 per cent, the atmospheric attenuation corrections were re-examined. It was found that considerable error resulted from neglecting the water band absorption of infrared when the distance of transmission was two miles or more. As the spectral distribution of energy has now been determined for the majority of shots, the amount of infrared absorption can be calculated. Application of this correction increased NRL's calculated values and brought them into accord with those of NRDL

for all shots except the King Shot at Operation IVY. NRDL's final data were also corrected for field of view and infrared absorption, although the corrections were less than 10 per cent due to the short path lengths compared to the visibility at continental tests. Measurements made from aircraft at air bursts involve an additional correction factor for the increased incident energy due to reflection from the ground below the burst. The amount of energy received by reflection is not readily calculable at this time. Experimental measurements have indicated that in Nevada it may be on the order of 50 per cent of that received by direct transmission for a receiver at an altitude which is large compared to the height of burst. At Eniwetok, the albedo of water is much lower than that of the desert. However, in low air bursts, the water shock passing through the water churns up a froth which produces an albedo that is considerably higher than that of the desert. It is estimated that the average effective albedo might approximate that of the desert. Therefore, a factor of 50 per cent was used to correct all of NRDL's data from airborne instruments in addition to the attenuation and scatter corrections.

  e. The corrected data of all three agencies for Operations GREENHOUSE, BUSTER, TUMBLER-SNAPPER and IVY are given in Table I. When data from more than one agency existed for a single shot, the average was generally used to determine the air burst scaling curve shown in Figure 1. UCLA data for SNAPPER Shots 6, 7, and 8 were not averaged with the NRL data because they were obtained as a check-out of the instrumentation in preparation for Operation IVY. The

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TABLE I

TOTAL THERMAL ENERGIES FOR VARIOUS ATOMIC DETONATIONS

Operation	Shot	Yield (KT)	TOTAL THERMAL ENERGY, KT		
			Agency		
			NRL	NRDL	UCLA
GREENHOUSE	Dog	82.9	17.6		
	Easy	46.7	12.3		
	George	214.5	39.0		
	Item	45.7	11.0		
BUSTER	Baker	3.48	1.3		
	Charlie	14.0	5.66	6.1	
	Dog	21.0	7.8	8.2	
	Easy	31.4	10.6	11.8	
TUMBLER- SNAPPER	1	1.05	0.46	0.51	
	2	1.15	0.485	0.49	
	3	30.0	9.0	10.9	
	4	19.6	6.0	6.9	
	5	11.7	3.9		
	6	11.4	4.25		5.9
	7	13.8	5.2		5.9
	8	14.0	4.95		4.95
IVY	Mike	10,000	1650	1500	1730
	King	550	80	240	

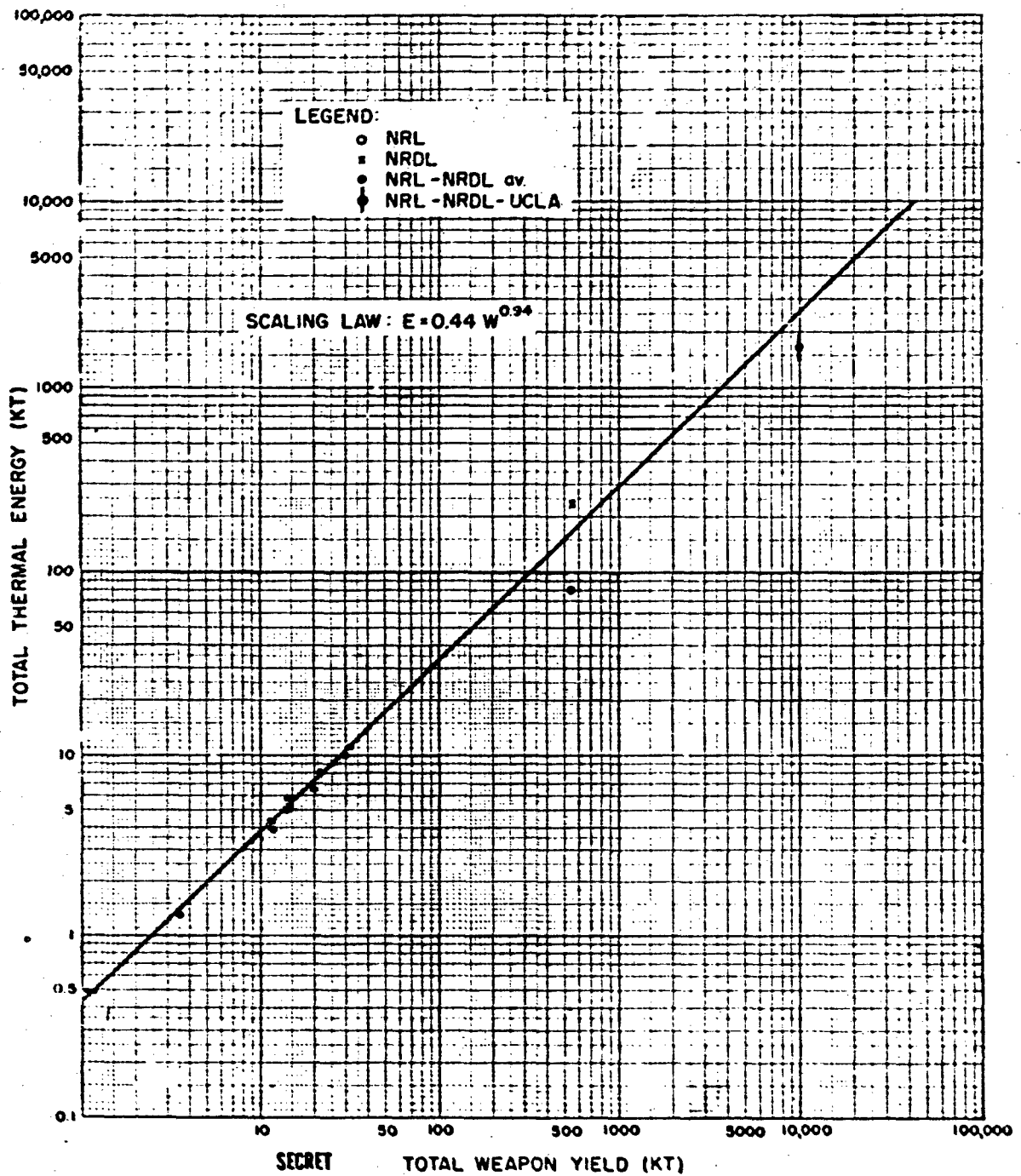Figure 1 TOTAL THERMAL ENERGY AS A FUNCTION OF TOTAL WEAPON YIELD

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GREENHOUSE tower shot data are shown in Figure 1 for comparative purposes only. The scaled heights of burst for these shots varied; all were considerably less than those of air bursts, and the thermal characteristics deviate significantly from those of an air burst. The low yield tower shots at Operation SNAPPER were very close to air bursts (as defined in TM 23-200), and the total thermal energies appear to be typical of air bursts. The slope of the air burst scaling curve is 0.94, and its equation is $E = .44W^{.94}$.[*] The accuracy is estimated to be ± 10 per cent for air bursts of radiochemical yields up to 100 KT. For detonations of radiochemical yields greater than several hundred KT, the error may be as great as 50 per cent.

f. The scaling law was extrapolated to the megaton yield range without any true high yield air burst data. While the data from the King and Mike Shots (total yields of which were 550 KT and 10 MT, respectively) are not directly applicable to the development of an air burst scaling law, they indirectly tend to substantiate it. Data on the King Shot were obtained by NRL with instruments located on the ground, and by NRDL from measurements made from aircraft flying above the burst. The estimates of total thermal energy for this shot were radically different. NRDL calculated 240 thermal KT, which is greater than predicted by the air burst scaling law. NRL

[*] E, total thermal energy released, KT.
W, total weapon yield, KT.
All symbols are given in Nomenclature, page 21.

determined the total thermal energy to be 80 KT, which is considerably less than expected from an air burst. Each thermal yield determination was consistent with the Stefan-Boltzman theoretical calculation using the average color temperature as determined independently by each laboratory (see Section 3). NRL's instruments viewed the side of the fireball, and those of NRDL, the top. The color temperature NRL saw was 3300°K. NRDL measured 5250°K. The King Shot was detonated at an altitude such that the fireball would just clear the ground when it reached its maximum radius. Fireball movies show that the fireball began to be flattened on the bottom at about 0.1 second after the minimum, and as it continued to grow it became almost hemispherical in shape. The time at which it began to flatten coincides with the time at which the reflected shock wave reached it. The distortion in shape of the fireball is characteristic of that produced by the passage of the reflected shock wave through the fireball. In view of the change of color temperature produced and the change in fireball area, which contributed to each of the energy measurements, it is reasonable that they should fall on either side of the air burst scaling curve, which passes through 160 KT at 550 KT total weapon yield.

g. The air burst scaling law was based on the premise that the fireball remained spherical throughout the major thermal pulse, which originally was thought to be limited to the height of burst at which the fireball did not touch the ground. It has become obvious that for thermal effects work an air burst is more properly defined

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as a burst at such a height that the reflected shock does not reach the fireball until after most of the thermal energy has been emitted. For any lower heights of burst, it may be expected that the energy received on the ground will be less than predicted by the air burst scaling law, and that the energy received above the burst will exceed that predicted, due to fireball distortion.

h. The Mike Shot was a surface burst. The thermal yield was calculated to be 1650 KT $^{+5}_{-15}$ per cent. This is higher than predicted for a surface burst on the basis of low yield surface bursts, but lower than the extrapolated air burst scaling law. This may be due to some thermal energy expenditure in heating and vaporization of the earth but very little obscuration of the fireball by dust. It was observed that the height of the dust skirt about the base of the fireball was very small compared to the radius of the hemispherical fireball. The diameter of the fireball at the base was equivalent to a 23 MT air burst. The integrated color temperature of the fireball surface was consistent with that of a low yield surface burst: about 3000°K. Since the rate of emission is proportional to $T^4 R^2$ *, the enlarged diameter or radius did not compensate for the decreased temperature, and the total thermal yield was one-third less than that predicted for an air burst of the same total yield.

i. In the "Capabilities of Atomic Weapons" (revised October 1952) it is stated that one-third the total thermal energy for an

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* T, absolute temperature, °K
  R, fireball radius, cm

air burst will be obtained from a detonation of the same radio-chemical yield burst on the earth's surface, and that for bursts intermediate to the surface and air, linear interpolation based on the scaled height of burst should be used. Analysis of the tower shot data given and the JANGLE surface shot results was the basis for these statements, and they are believed valid for detonations up to approximately 250 KT in yield. However, the Mike Shot data make it evident that they do not apply to megaton yield weapon detonations. It is recommended, for the present, that two-thirds the air burst thermal yield be used for the thermal yield from surface bursts of megaton yield weapons. For yields intermediate to 250 KT and 1 MT, the factor may be expected to be between one-third and two-thirds.

2. Time-Intensity Characteristics

a. The radiant energy from the fireball is emitted at varying rates, as described by the time-intensity curve, which is characterized by an extremely rapid rise to the first maximum and decline to the "minimum", followed by a moderately rapid rise to the second maximum and a gradual decline. The second portion of the time-intensity curve, during which 99 per cent of the energy is emitted, is of primary interest.

b. NRL and NRDL measured the variation of radiant intensity with time at BUSTER, TUMBLER and IVY tests. For the BUSTER series, NRDL determined the second pulse shape by differentiating the integrated calorimeter curve. At the later test series, NRDL

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obtained direct time-intensity records with a foil radiometer with a time constant of 13 milliseconds in addition to the differentiated calorimeter trace. NRL obtained direct time-intensity traces with bolometers, which have a time resolution of less than 50 microseconds and resolve the first thermal pulse. The NRL traces enable the determination of the time of the minimum, as well as the shape of the second pulse.

c. For the purpose of determining the scaling in time of the thermal pulse, the times of the minimum and the second maximum were selected from the time-intensity records.

d. Figure 2 gives the time of the minimum plotted against radiochemical weapon yield for yields ranging from 1 KT to 10 MT. The curve was based on NRL data for Operations GREENHOUSE, TUMBLER-SNAPPER, and IVY. The maximum deviation of data from the curve with time was less than 10 per cent over the entire yield range. The slope of the curve is 0.5. The data used include tower as well as air burst data. It is concluded that the time of the minimum scales as the square root of the yield for any size air burst and for near air bursts, represented by tower shots.

e. NRDL BUSTER, TUMBLER, and IVY data were used along with NRL TUMBLER and IVY data to determine the variation of the time of the second maximum with yield, given in Figure 3. This curve shows that the time of the maximum also scales as the square root of the yield for air bursts and near air bursts of 10 KT or greater, and for large yield surface bursts as well. The data shown in Figure 3 show that
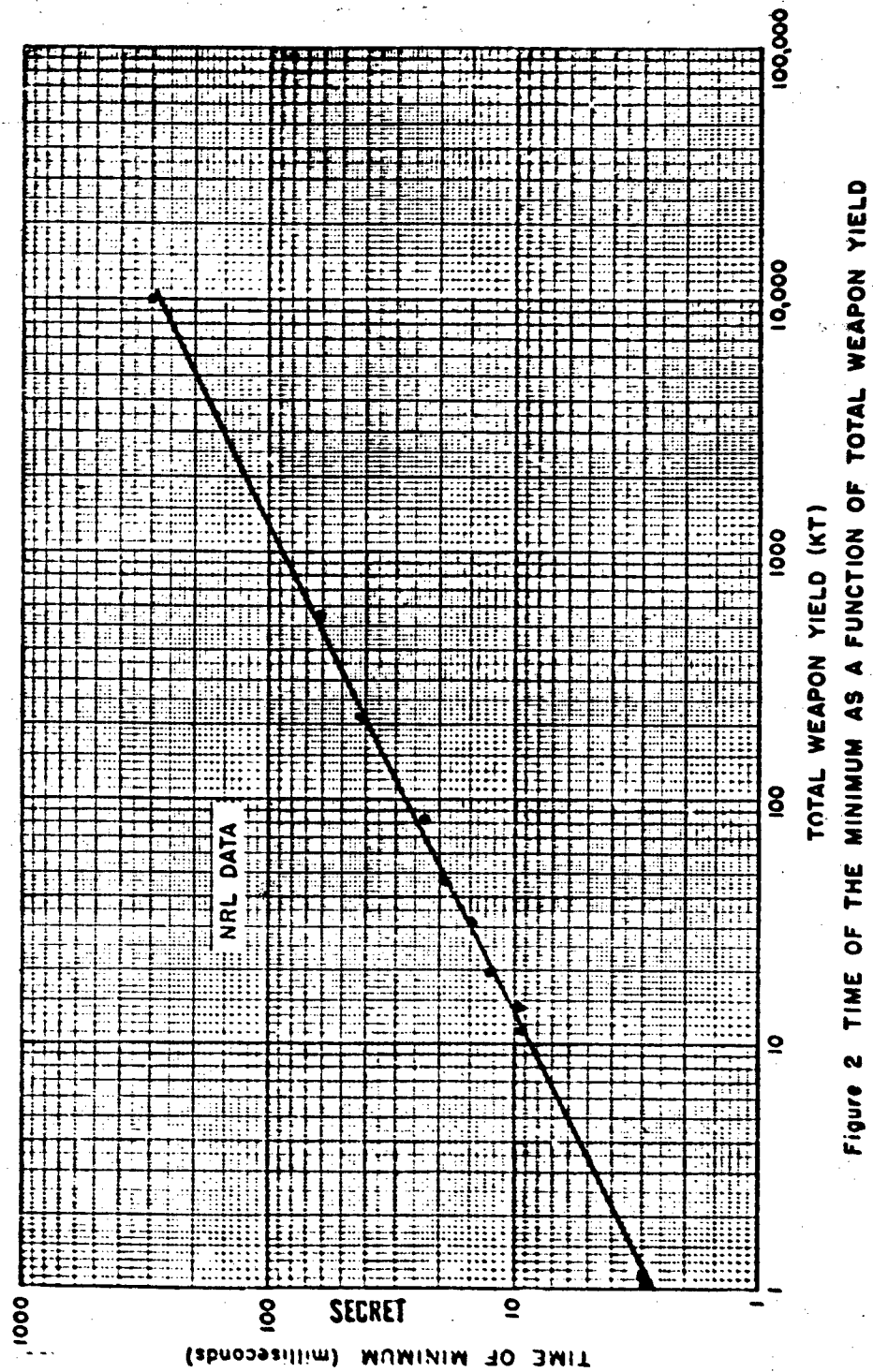
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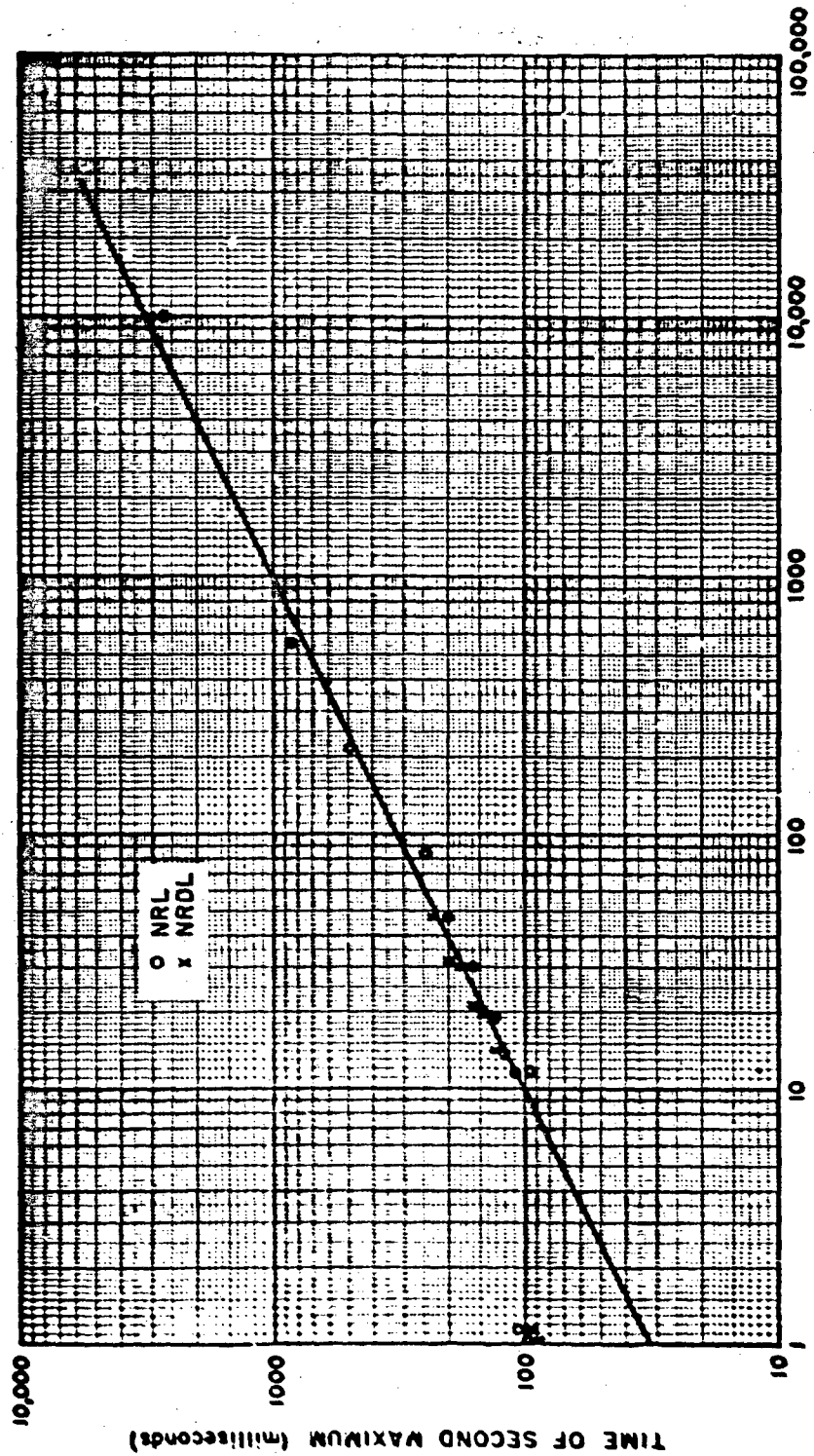Figure 2 TIME OF THE MINIMUM AS A FUNCTION OF TOTAL WEAPON YIELD

Figure 3 TIME OF SECOND MAXIMUM VS TOTAL WEAPON YIELD

for either of the two systems of measurement (NRDL or NRL), the

maximum deviation is less than 10 per cent, but the NRL times seem

to be consistently lower than NRDL's. Since this difference in

systems has not been resolved, the curve is drawn between the two

sets of data. The presently available data for air bursts of less

than 10 KT yield are not necessarily typical of operational weapon

characteristics. Although the total energy emitted in these low

yield detonations appeared to scale, an extended thermal pulse and a

change in the spectral distribution of energy were observed. It has

been postulated that these changes were due to the high mass to yield

ratio, which was characteristic of these particular devices. It is

expected that the scaling laws given for air bursts may apply to very

small yield weapons of an operational design.

     f. A number of intensity-time traces from both agencies,

for air bursts whose yield ranged from 14 KT to 10 MT, were plotted

in the form: I/I_{max} vs t/t_{max} to determine a generalized shape of

the second portion of the thermal pulse, after the minimum.

     g. Figure 4 shows the normalized curve of the thermal pulse

for any yield air burst. The accuracy of this curve in I/I_{max} is

estimated to be ± 15 per cent.

     h. If the scaling of intensity and time are known, the

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* I, radiant intensity, cal/cm^2-sec.
  I_{max}, maximum radiant intensity, cal/cm^2-sec.
  t, time interval after detonation, seconds.
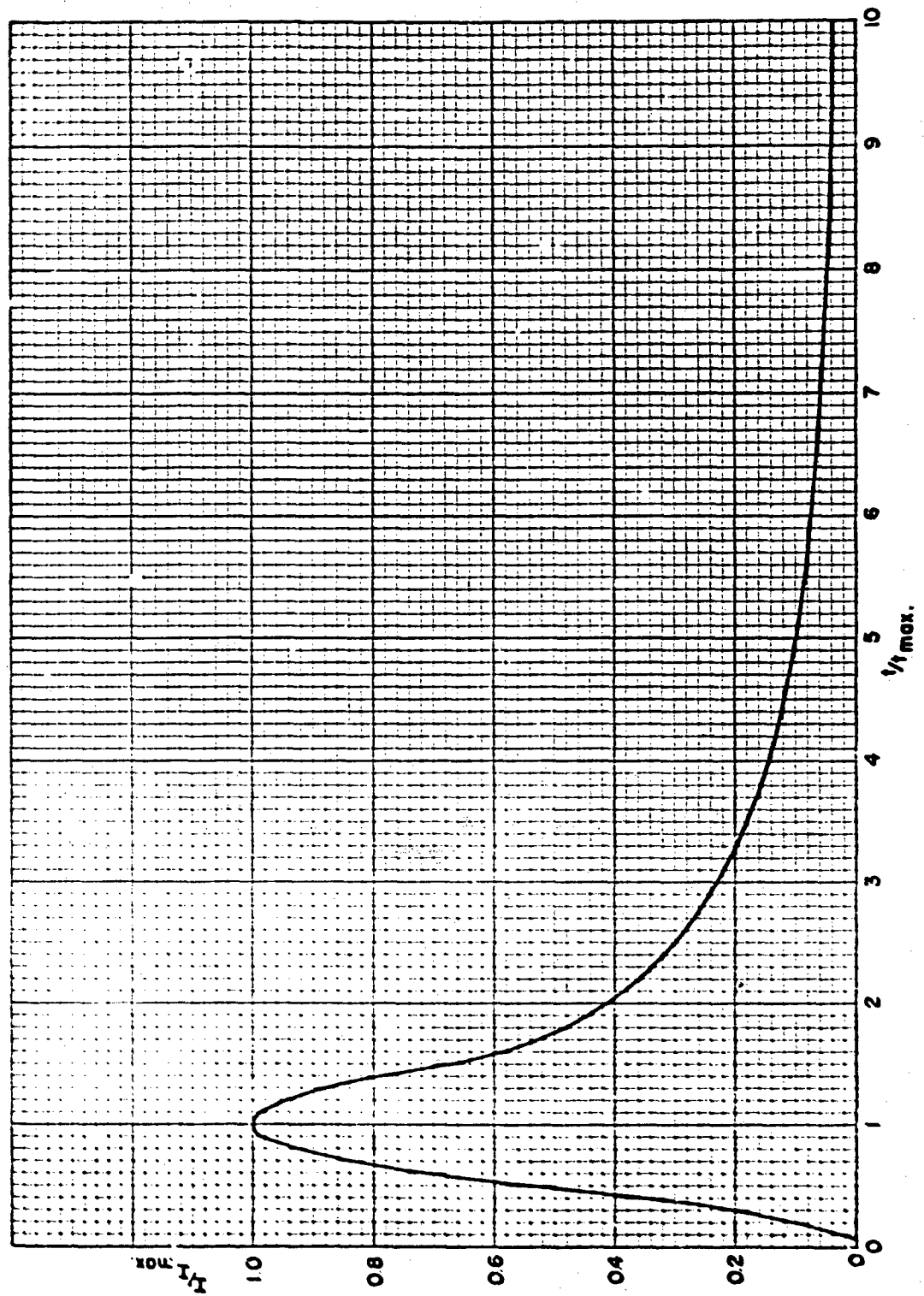 t_{max}, time of the maximum intensity, seconds.

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Figure 4 NORMALIZED PULSE SHAPE

normalized curve may be used to draw a generalized time-intensity curve for any yield weapon, in terms of IW^n and tW^m. It has been well established that time scales as the square root of the ratio of the yields. The scaling of the maximum intensity has been studied, but due to the scatter of the data it is still somewhat tenuous. For planning purposes, it is recommended that square root scaling be used for the intensity, with the understanding that this is subject to change as more data become available. The generalized curve is given in Figure 5.

3. Spectral Distribution

a. Since the response of most targets to thermal radiation is dependent upon the wave length of the radiation, as well as the intensity and total energy incident, a continuing study has been made of the spectral characteristics of thermal emission.

b. NRL has measured energy distribution in the ultraviolet and visible with spectographs which have a 5Å resolution at time intervals of 200 microseconds for GREENHOUSE and TUMBLER-SNAPPER and 2000 microseconds at IVY. NRDL has measured the energy in five broad spectral regions: .22 to 4.5μ; .36 to 2.5μ; .53 to 2.5μ; .64 to 2.5μ; and .95 to 2.5μ, integrated with time throughout the pulse. NRDL has also measured the time variation of energy distributed in these bands. UCLA made detailed spectral studies of the variation of radiant flux density with time at several wave lengths and in several wave bands. At Operation IVY measurements were made at four wave lengths: .35, .45, .75, and .95μ, and in two wave bands: .35 to 2.6μ, and .91 to 2.5μ. At TUMBLER-SNAPPER

$I_{max} = 3.85 \; W^{1/2}$ (KT/sec)

$t_{max} = 0.032 \; W^{1/2}$ (seconds)

$t \; W^{-1/2}$ (seconds per $KT^{1/2}$)

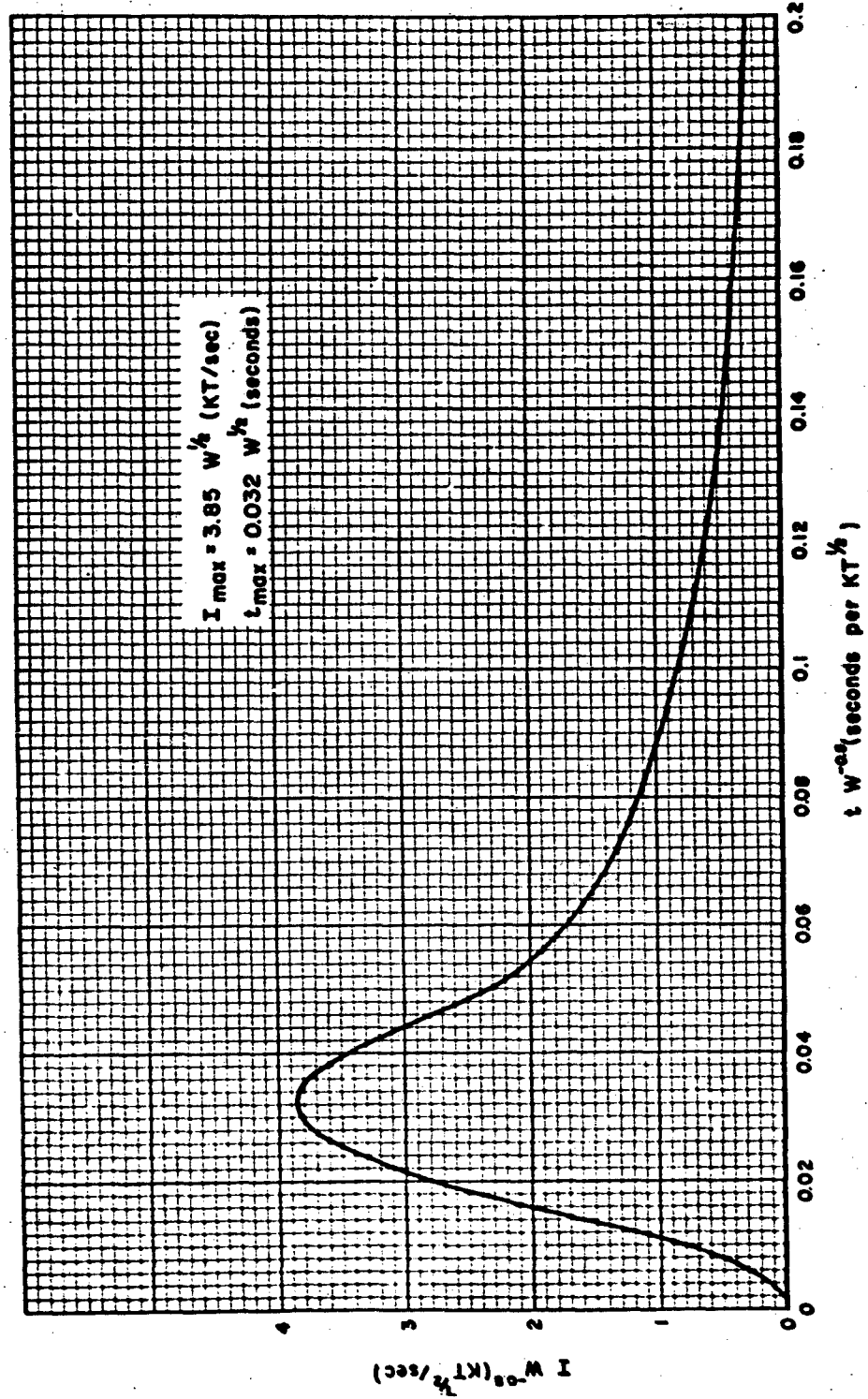$I \; W^{-0.8}$ (KT$^{1/2}$/sec)

Figure 5 GENERALIZED THERMAL PULSE

(Shots 7 and 8), measurements were made at five wave lengths: .35, .48, .55, .75, and .95 μ.

        c. The shape of the integrated curve of energy density as a function of wave length was compared with black body curves, as determined by Planck's equation, for various temperatures. NRL found that the shape of the curve in the ultraviolet, beyond the 3000Å ozone cut-off point, and in the visible, for a given burst, could be fitted to a black body curve for a specific temperature. Thus, a temperature can be assigned to the energy distribution curve, and this temperature is called the "color temperature". The NRDL and UCLA results provided some additional data on distribution in the infrared which, in general, supported the NRL data. A color temperature was thus assigned to each detonation. The temperatures are given in Table II. It was concluded that as a general rule the average color temperature for air bursts is $6000°K \pm 500°$. The effect of introducing mass in excess of the air into the fireball is to lower the average surface temperature. Tower shots and surface shots are affected by the earth and material of the tower taken into the fireball. The average temperature for a surface burst is around $3000°$ K, and for a tower shot, usually between 3000 and $6000°K$.

        d. For an air burst, 55 per cent of the bomb's thermal radiation energy is in the ultraviolet and visible, (.3 to .75μ), and 45 per cent in the near infrared, (.75 to 3μ). For a surface burst, 12 per cent is in the visible and 88 per cent is in the infrared.

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TABLE II

COLOR TEMPERATURES* FOR VARIOUS ATOMIC DETONATIONS

| Operation | Shot | Type of Burst | Color Temperature, °K | | |
| | | | Agency | | |
			NRL	NRDL	UCLA
GREENHOUSE	Dog	Tower	4500		
	Easy	Tower	4000		
	George	Tower	3000		
BUSTER	Baker	Air		5600	
	Dog	Air		6300	
	Easy	Air		5600	
TUMBLER-SNAPPER	2	Air	5000		
	3	Air		6000	
	4	Air		6000	
	7	Tower	4700		4200
	8	Tower	6000		4200
IVY	Mike	Surface	2600		2900
	King	Air	3300	5250	

* Equivalent black body temperatures.

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e. It has been further shown that the use of the average color temperature in the Stefan-Boltzman law, $\frac{E \times 10^{12}}{4\pi R^2 t_o} = \sigma T^{4}$ *, gives the measured total thermal energy E within 10 per cent. The fireball radii were determined from EG&G measurements of the radius at the time of the minimum, multiplied by a factor of 1.5. This is an empirical rule of thumb for the radius at the time of the maximum intensity. Its accuracy will not be known until an analysis of late fireball diameters becomes available. However, it will be noted that the energy calculation by the Stefan-Boltzman law is relatively insensitive to radius errors as compared to color temperature which appears as the fourth power. Since the accuracy of the color temperature estimates is only $\pm$ 10 per cent, such calculations are at best only a rough check.

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* σ, Stefan-Boltzman constant in cal/cm^2 - sec - ($^\circ$K)^4.
t_o, total duration of the thermal pulse, seconds.

NOMENCLATURE

E = Total thermal energy, KT

W = Total weapon yield, KT

R = Maximum fireball radius, cm

T = Absolute temperature, $°K$

t = Time interval after detonation, seconds

t_o = Duration of the thermal pulse, seconds

t_{max} = Time of the maximum intensity, seconds

I = Radiant intensity, cal/cm^2-sec

I_{max} = Maximum intensity, cal/cm^2-sec

σ = 1.35 x 10^{-12} cal/cm^2-sec-($°K$)^4